Assessment of Ship Emissions in Coastal Waters using Spatial Projections of Ship Moves (Ship Density) and Port Congestion Data

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ABSTRACT

Emissions from ships are having a growing impact on acidification of the oceans and eutrophication of enclosed seas. Ships are increasing in number and size and coastal regions that provide supporting services to shipping suffer from the impact of air and water pollution. Air emissions have been proven to have a direct impact on human health, climate change, acidification of the water and disruption of ecosystems and habitats.

The International Maritime Organization (IMO) is adopting new measures for the reduction of emissions from ships. From January 1st 2020, the global limit for sulphur in marine fuel was reduced to 0.5% by mass, while heavy fuel oil can still be used by vessels retrofitted with abatement technology that complies with the new regulations. Emission Control Areas (ECA) and all EU ports already have reduced sulphur limits to 0.1% by mass.

The IMO is limiting nitrogen oxides (NOx) as all ship engines built after 2016 should comply to Tier III regulations, however, those ships older than 2016, still operate outside the ECAs. A novel methodology has been developed to calculate emissions from ships and applied to understand the different contributions of Tier 0, I, II and III category ships, to total emissions during their time in port.

This paper presents the novel methodology behind the computational model called: Ship Emissions Assessment (SEA) model. The methodology behind the SEA model analyses ship tracks (density maps) of different ship types, to extract data for activity-based ship emission calculations. The SEA model calculates emissions using ship activity phase data to give an understanding of locality where emissions are happening.

Ships are clustered in groups by ship type, which share the same ship track patterns. Those patterns (ship density maps) can improve the understanding of which spatial areas are at highest risk and need to be assessed for the impact of air borne emissions.

The novel methodology presented, enables the use of ship track patterns available from AIS data maps to estimate airborne emissions from ships in coastal areas for assessment. A case study has been conducted using the computational SEA model, to calculate emissions from containerships calling to the Port of Trieste.

KEYWORDS

Sustainable shipping, Ship Emissions, Emission Calculation from AIS data, Coastal water emissions, Port Energy Efficiency, Spatial Emissions Port

INTRODUCTION

International Maritime Organization (IMO), global regulations to reduce air borne pollution from ship engines, require all engines built after 2016 to comply with Tier III standards. The global limit for sulphur content in ship fuel oil is replaced by a new limit of 0.5% by mass from 1st January 2020, (old limit was 3.50%).

The increased need of shipping industry stakeholders to understand and further control airborne pollution from ships engines, in particular in the areas of high population density in port city areas, leads to the need to assess the air borne pollution from ships and understand this spatially. This is a particular problem because emissions are not measured at individual ships and have to be estimated, however they are highly dependent on the fuel type, engine type and engine load conditions. Load conditions can be associated with ship speed and activity phase, like manoeuvring, anchoring or berthing.

Many existing methods [1],[2],[3] & [4], that estimate emissions are expensive and time consuming or demand high levels of precise data obtained empirically by measurements on ships. There is a need for simplified method for ship emission estimates, to keep up with new IMO requirements (reduction of 50% by 2050), as data for decision making needs to be more transparent and accessible to all stakeholders in the shipping process. The methodology for ship emission estimation has been developed, that provides emission to the air calculation and spatial understanding of where pollution from ships is taking place.

The aim of the novel method is to estimate emissions from ships and provide spatial understanding of airborne pollution distribution, using widely available data packages of historic ship tracks and calls to port information.

The highest impact on human health in port cities, comes from oxides of nitrogen (NOx), that are directly associated with the formation of ground level ozone and particulate matter (PM). Substantial evidence shows that even short-term exposure to the $PM_{2.5}$ content of ship emissions is associated with increased cardiovascular mortality in the region of port cities [5].

A reduction in SOx emissions has already started to be recorded, however regulations are still not limiting nitrogen oxides (NOx) outside the Emission Control Areas. Formation of Nitrogen oxides is not affected by limiting sulphur content in the fuel, as NOx is formed in the engine in a secondary process, after combustion, and due to high temperatures likely to develop in diesel engines (expanding by combustion).

Regulations were set to identify engine types according to the year of build and emission standards. All engines built after 2016 should comply to the stricter Tier III standards of the IMO NOx regulations. From 1st January 2021, all ships passing through NOx Emission Control Areas such as the Baltic Sea and the North Sea will have to comply to the Tier III standard, which is expected to reduce NOx emissions by 70%.

Methods for calculation of shipping emissions have been widely developed since the Third IMO GHG Study [6]. Some methods provide high precision in emission estimates but require complex data processing, high level of expertise and long observation periods [7] to [11]. There is a need for user friendly ship emission assessment method, that would be at disposal to all stakeholders in the shipping industry. Therefore, the model has been developed for rapid ship emission estimates, as explained in the next section.

Methodology behind the Ship Emissions Assessment (SEA) model

The SEA model methodology analyses spatial distribution and different location of ship traffic, to understand the length of time that ships spend in different Activity Phases. Activity Phases are defined as cruising, anchoring/berth (hoteling) and manoeuvring
The SEA model is developed for calculation of emissions from ship with diesel engines using conventional fuels, as presented in Figure 1.

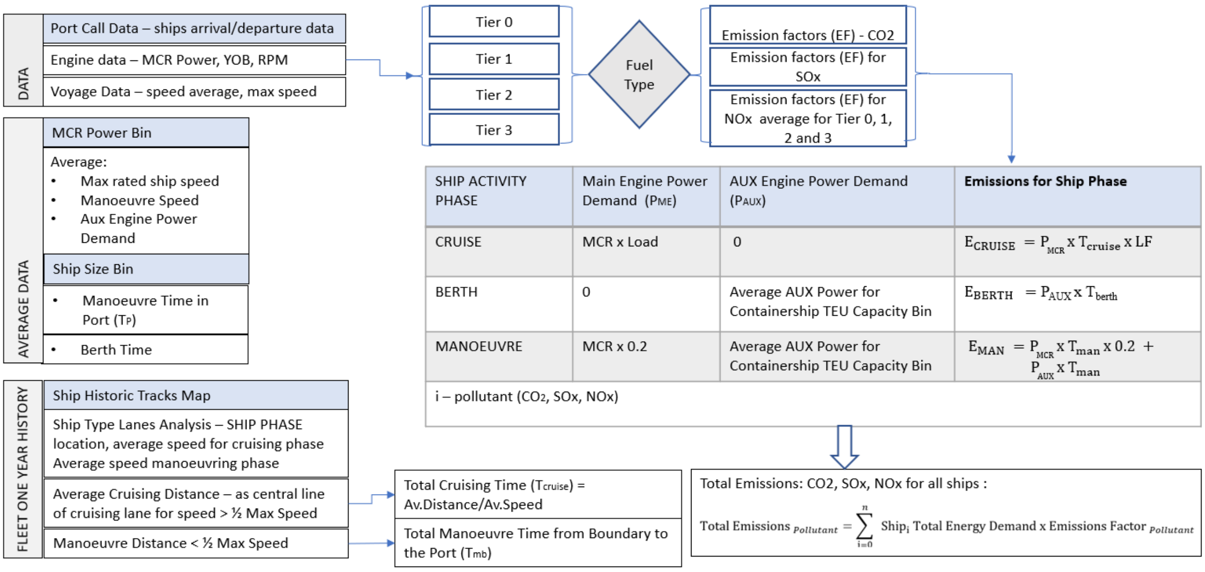

Figure 1: Ship Emission Assessment Model (SEA), diagram

There are 4 key steps in the methodology, and these are explained next.

Data:
Port calls data: times of arrivals and departures of ships (first seen and last seen times), time ships spent in berth (at zero speed), ships names, containership maximum capacity (TEU).
Engine Data: Year of Built (YOB), Maximum Rated Power, RPM, retrofit information (SO_x or NO_x scrubber, date of installation), obtained from Clarkson's System.
Voyage Data – refers to the last log of the voyage: Voyage Speed Average, Voyage Speed Maximum, obtained from Marine Traffic System; statistics of world containership population [6]. Maximum Rated Speed (V_{max}), Averaged Sea Speed for containership capacity bins (V_{sea})

Activity data:
Ship Historic Tracks Map: Averaged Distance in cruising and manoeuvring phase.
With Spatial distribution revealed through ship tracks (examples presented in Figure 4, 5,6 and 7), the SEA Model calculates emissions for the main engine, based on ship activity phases energy demand. Resolution enables spatial understanding of shipping lanes density of ship moves per kilometer square. Shipping lanes are distinguished and measured to establish distances, regardless the direction of traffic, for ship types getting in and out of the port.

Assumptions and Estimates:
Auxiliary Engines Power Demand: For auxiliary engines power demand is assumed using statistical average values, for different ship activity phases [6].
Average Maximum Rated Speed: Is statistical average for containership capacity bin [6]. These values are taken from averaged empirical data in IMO statistics for ship types, as not available

in ship data sets. This simplifies the data needed to run the SEA model and enables quick processing of large numbers of ships.
Engine load: It is assumed that auxiliary engines are at low load during cruising phase, high load during manoeuvring and medium load in port, as presented in Figure 1.

Emissions for Ship Activity Phase

Energy demand is estimated for each ship activity phase, for main engine and auxiliary engine as presented in equations 2, 3 and 4. Total energy demand calculated by equation 1, is multiplied by emission factor as presented in 5.

SHIP ACTIVITY PHASE ENERGY DEMAND:

Ship Total Energy Demand: $E_{TOTAL} = E_{CRUISE} + E_{MAN} + E_{BERTH}$ (1)

$$E_{CRUISE} = P_{MCR} \text{ x } T_{cruise} \text{ x } LF \quad (2)$$
$$E_{MAN} = P_{MCR} \text{ x } T_{man} \text{ x } 0.2 + P_{AUX} \text{ x } T_{man} \quad (3)$$
$$E_{BERTH} = P_{AUX} \text{ x } T_{berth} \quad (4)$$

P_{MCR} – main engine maximum rated power
P_{AUX} – auxiliary engine power demand average for ship activity phase
T_{cruise}, T_{man}, T_{berth} – The length of Time ship spends in activity phases is calculated as explained by equations 6 and 7 and further in this section.

$$\text{Total Emissions}_{Pollutant} = \sum_{i=0}^{n} \text{Ship}_i \text{ Total Energy Demand x Emissions Factor}_{Pollutant} \quad (5)$$

Pollutant – CO_2, SO_x and NO_x

Emissions Factor $_{Pollutant}$: Pollutant emission factors for CO_2, SO_x and NO_x , expressed in g/kWh are according to the Third IMO GHG Study, [6].
For NOx, emission factors are different for engine tier bins, Tier 0, I, II and III. Engines identified as retrofitted with scrubbers for NOx, where also considered as Tier 3 engines.

Time for cruising (T_{cruise}) is calculated as:

$$T_{cruise} = \frac{\text{Average Distance}_{cruise}}{\text{Voyage Speed Average}} \quad (6)$$

Where Average Cruising Distance is obtained from Ship Historic Tracks Map as explained in the section: “Application of the SEA Model to containerships calling to the Port of Trieste”. Voyage Speed Average is obtained in the Voyage Data, as average speed for the vessel’s last log (last port to current port).
Time manoeuvring (T_{man}) is calculated as:

$$T_{man} = \frac{\text{Average Distance}_{man}}{V_{sea} \text{ x } 0.3} \quad (7)$$

Time at berth (T_{berth}) is retrieved from Port Calls data.
Main engine load is calculated using the equation 7, where "n" for containerships is assumed to 3.5, as suggested by [12].

Comparing the SEA Model to Port Emission Estimate Model results

Conventional ship emissions estimate methodology suggested by [6] was used to understand to what extent are the SEA model results comparable to other methods.
The method used for comparison, (Port Emission Estimate Model [6]), calculates the distance between AIS (Automatic Identification System) points of call taken from Clarkson's system, from the point when ship has entered the 15nm port boundary, until the exit from the boundary.

For 20 individual container ship voyages, the amount of CO_2 emission has been calculated using actual distance between each AIS point of call.

The results of emission estimates for CO_2 for both methods were compared for 20 voyages. Voyages are calls to the port, from entry to exit of researched 10nm boundary.
Auxiliary engine power demand estimates remained unchanged for both methods, however estimated distances for ship phase impacts the results of emissions from auxiliary engines, causing them to be different for each method.
Results of total emissions are compared in Figure 2.

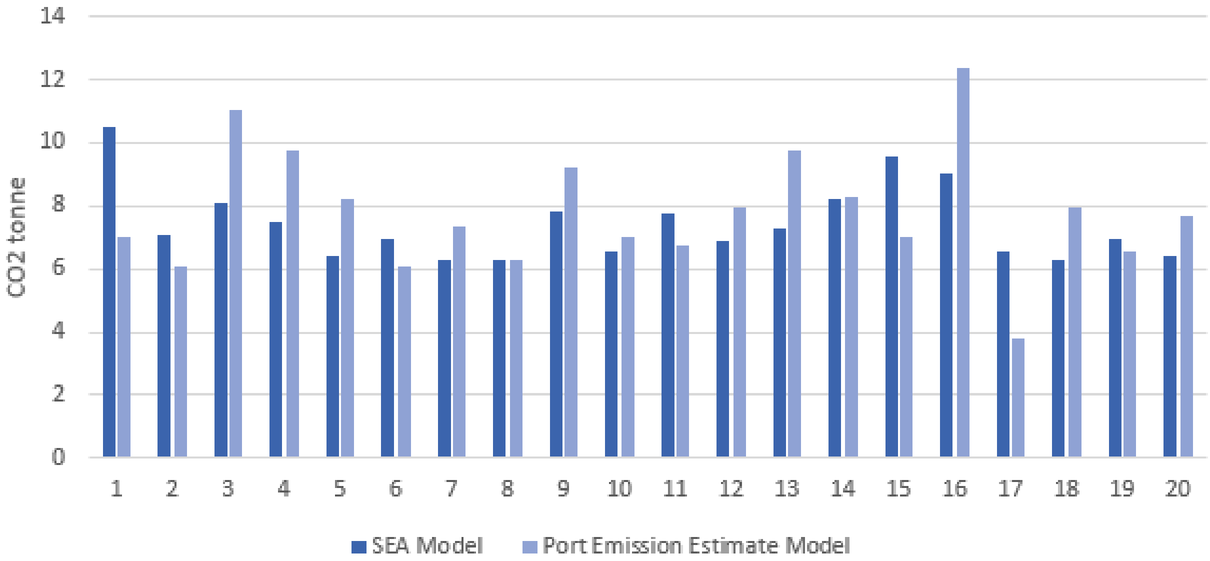

Figure 2: Results compared between the SEA Model and the Port Emission Estimate Model

It can be observed that for the single ship voyage, (port calls measured as voyage in and out of the 15nm port boundary), emission estimates using the SEA Model, could differ from conventional Port Emission Estimate method [6].

However, when Port Emission Estimate Model emissions per voyage are aggregated, variations that were scattered equally to positive and negative side of the mean, will cancel out. Results for the SEA method using the average of aggregated voyage distances from the ship tracks spatial map, compare well to Port Emission Estimate Model aggregated results of total emissions from all voyages, with less than 5% difference.

It can be concluded that results of the SEA Model compare well to conventional methodology emission estimates for large datasets (minimal aggregation of emissions for 20 ship voyages is possible). This is demonstrated by
Figure **3**, which shows deviation of results for the two compared methods, around the mean value of Port Emission Estimate Model results. Validation (Port Emission Estimate Model) will provide more accurate distance for single ship voyage emission calculation, as it uses actual voyage distance as measured between AIS points of call. The SEA model uses averaged distance and result's values are scattered equally to positive and negative side of the Port Emission Estimate Model mean value.

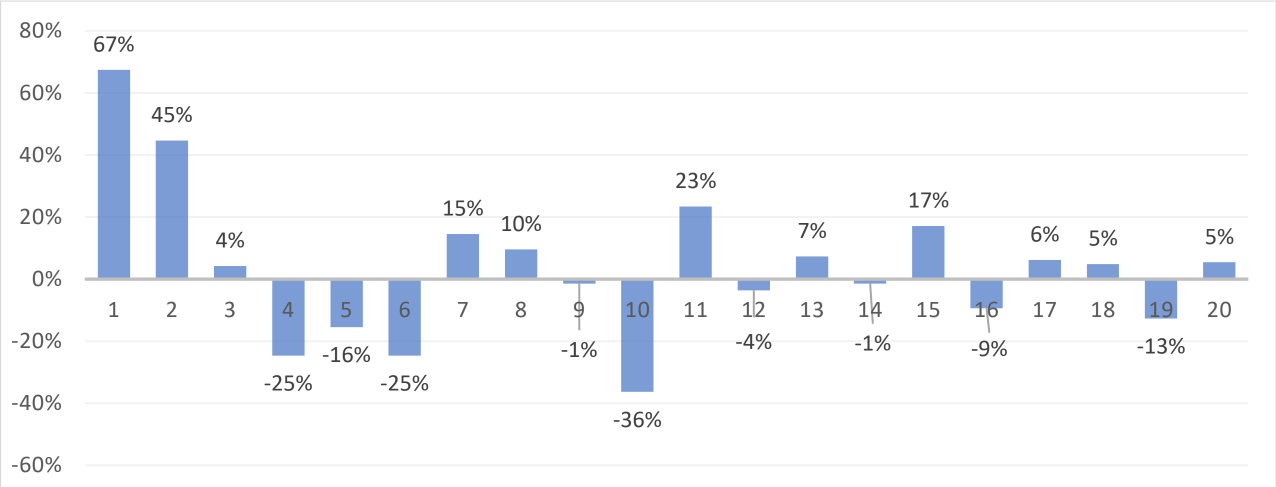

Figure 3: Difference in results of emissions of CO_2, method compare for SEA Model and the IMO Port Emission Estimate Model.

Once the SEA method results (total emissions for all voyages considered) are summed up, the differences in results cancel each other out, and the result differs from PEM method by less than 5%, as presented in Table 1.

Table 1: The SEA Model results compare to the Port Emission Estimate Model (Validation method) results

	SEA Model	PEM Method	Result Difference (tonnes CO_2)	Result difference %
Total Emissions all voyages [tonnes of CO_2]	148.31	156.07	7.75	4.97%

Application of the SEA Model to containerships calling to the Port of Trieste

This research uses the Port of Trieste in the Adriatic Sea as its case study. As the Port of Trieste is the last port of call for containerships in the Adriatic Sea, 95% of historic containership movements recorded in ship track maps, will correspond to ships calling to the Port of Trieste. Figure 4 shows spatial congestion of container ship tracks throughout 2017, available through the Marine Traffic system.

The identification of shipping lanes from the ship tracks map is simple for this specific locality as most containerships using the lanes on the map, call to the port. As Figure 4 presents, only 5% of ships take top two lanes, leading to Monfalcone yard.

Apart from fishing boats and pleasure yachts, most merchant ship types have route patterns, therefore, it is possible to understand ship moves and distances of ship cruising and manoeuvring lanes, from historic ship track maps.

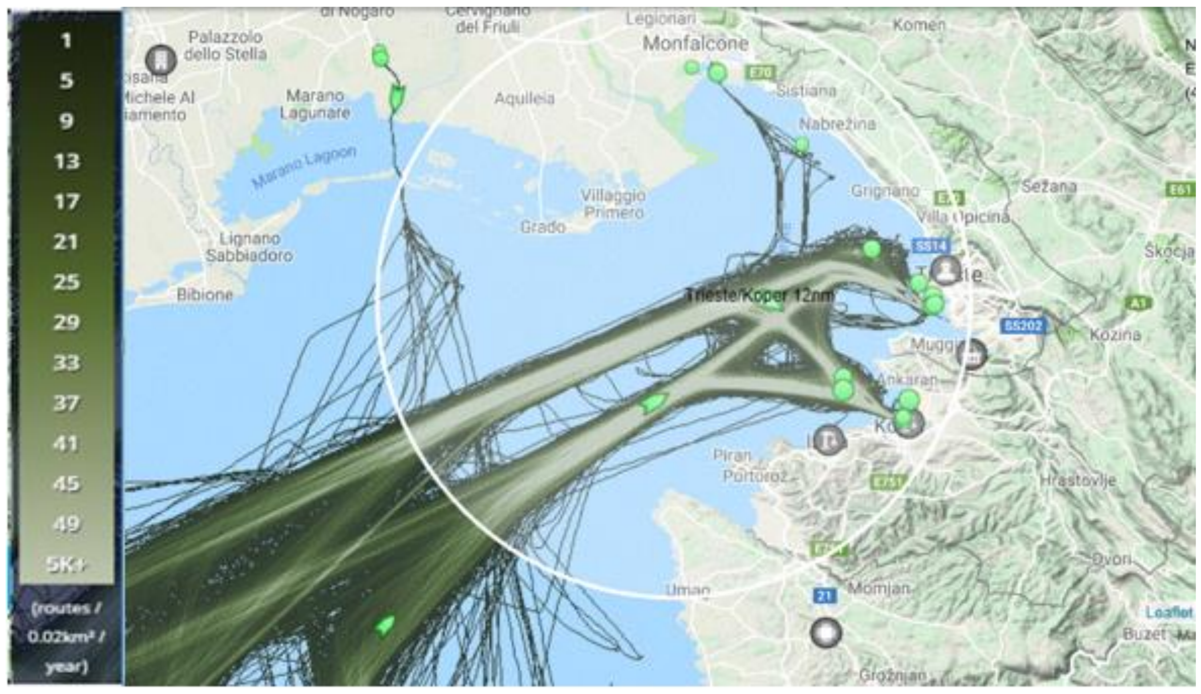

Figure 4: Historic Containership tracks (ship density) in 2017, 15nm boundary of the Port of Trieste [13]

Traffic lanes of highest density of containership’s moves per square kilometre were identified. Vessels using lanes were then analysed, to understand patterns in containership navigation and ship activity phase locations along the lanes.

The sample of ships listed in the Port calls data, were chosen to represent all Maximum Rated Power bins, Ships from the sample were observed to understand vessel speed patterns and ship activity phase spatial distribution. The size of the sample was concluded when a repetitive pattern was established, and ships activity phases localized.

Two lanes were identified and measured along the central line of highest congestion, as shown in Figure 5 and 6.

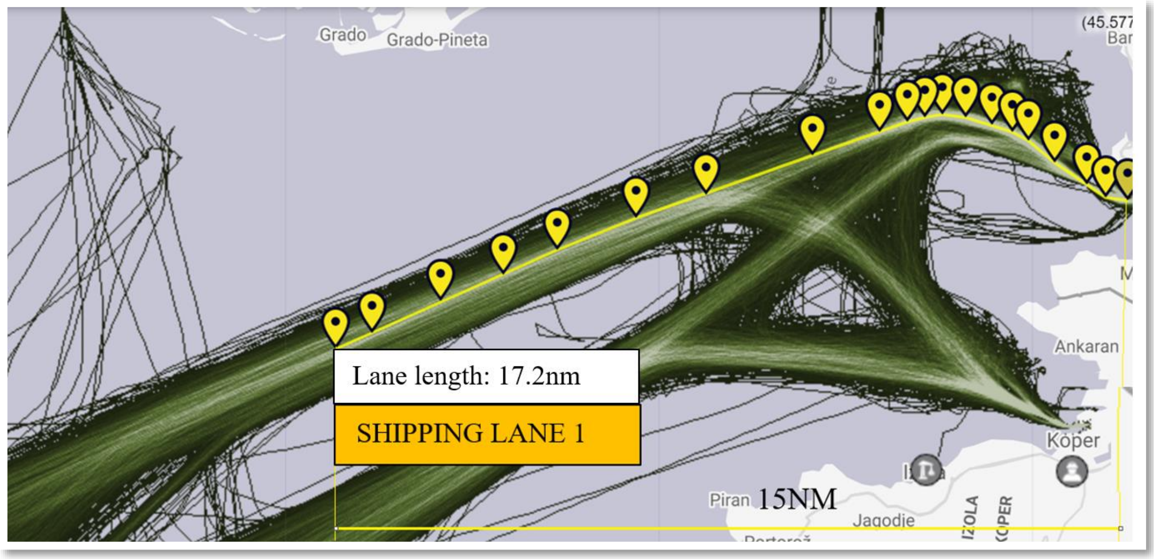

Figure 5: Shipping Lane 1, 17.2nm average length [13]

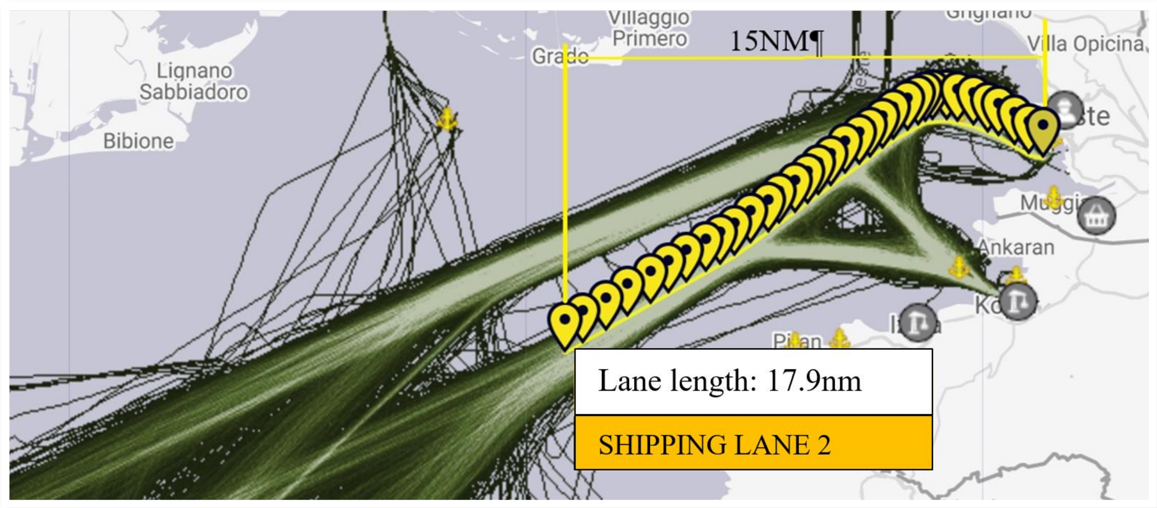

Figure 6: Container ships shipping lane 2, length: 17.9nm [13]

First two lanes were added together as averaged voyage distance, one was assumed as the entry lane and the other as berth and port exit lane.

Third shipping route Figure 8 is measured from boundary edge to the anchorage. This route is measured to the approximated central point of the anchorage zone. Anchorage zone is better analysed, if ship points of call are observed (Figure 7), rather than ship tracks projected as connected lines between the points of call to AIS.

Ships from database were selected according to the length of time spent in the port. Ships taking more then 24h for Time in port, were assigned Lane 3 distance, as it was assumed those ships were anchored. For regular analyses of same ports, further research is needed to analyse typical port processing time for different containership capacity bins.

Figure 7: Ship anchorage analysed using points of call historic spatial map [14]

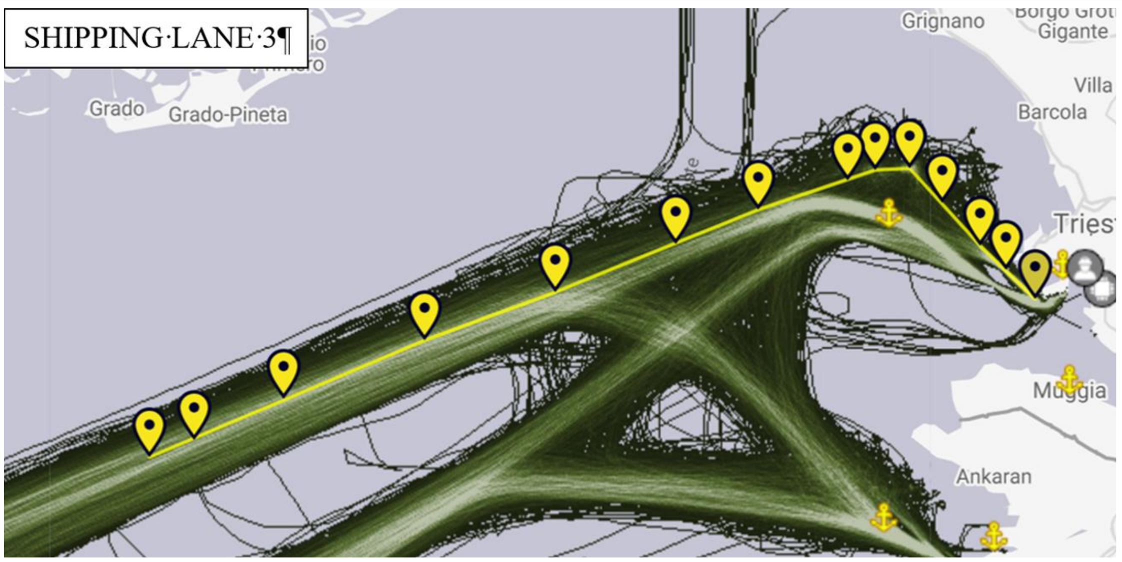

Figure 8: Third route leading to the anchorage and further to the port, 4.5nm was added to the Lane 1 length [13]

The point where speed becomes less than half of the average sea speed for the area is assumed to be the start of the manoeuvring phase. Manoeuvring distance is subtracted from the averaged voyage distance to get averaged cruising distance.

RESULTS

Emissions were calculated for a period of 7 months (mid-March to mid-October 2019), for 77 containerships calling to the Port of Trieste, in 377 voyages.
Results are presented in Table 2.

Table 2: Port of Trieste Emissions for sample of 377 containership voyages (7 month period)

	Trieste
CO_2 [tonne]	7,584.75
SOx [tonne]	7,743.07
NOx [tonne]	129.90
Total voyages researched	377
Total number of ships	77
Total DWT	16,586,021
Max TEU Capacity Total	1,429,234
Time period	March - October 2019

Ships were analysed for engine type Figure 9, according to Tier III standards of the IMO NOx regulations. Emission factors were assigned accordingly to [6], using the criteria in Table **3**.

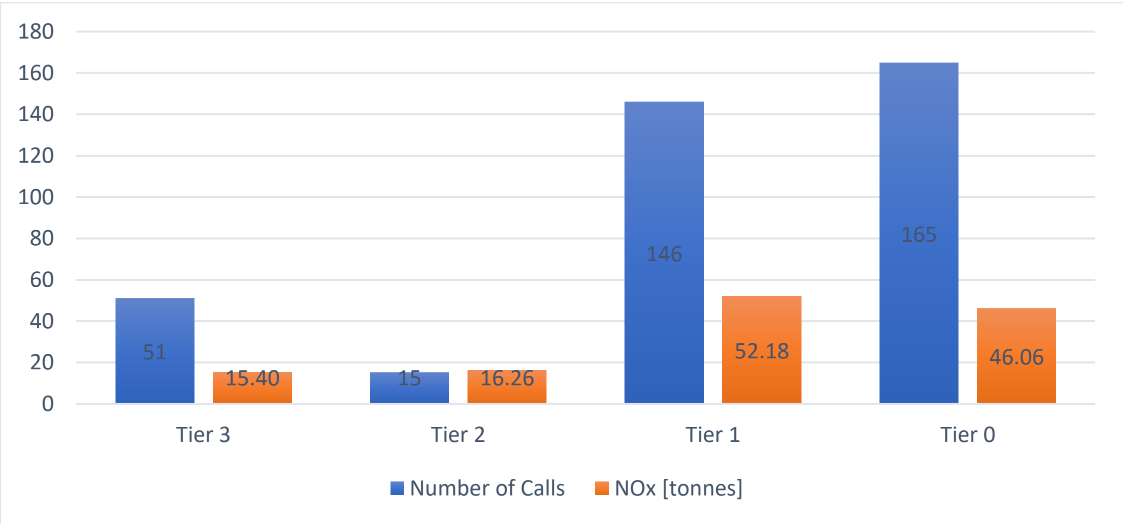

Figure 9: Engine Tier Contribution to NOx Emissions – Port of Trieste

Table 3: Engines classified according to IMO NOx engine Tier III standard

Engine Tier	*Maximum Rated Power*	*Year of Built*
Tier 0	MCR>5MW	1990 - 1999
Tier 1	MCR>130kW	2000 - 2010
Tier 2	MCR>130kW	2011 - 2015
Tier 3	MCR>130kW	2016 - today

Results show distribution of emissions from 377 voyages, of 77 different container carriers, in groups of different Tier engine standards. The highest contribution to emissions comes from Tier 0 and Tier 1 type ships. Tier 0 type ships contribute 35% of overall NOx emissions and

Tier 1 is even higher at 40%. Total emissions of ships older than 2010 is 75% out of all emissions.

CONCLUSION

Conventional methodologies for ship emissions assessment, do not offer a simple to use tool for spatial distribution of emissions and understanding of where emissions take place. A new ship emissions assessment model presented in this paper offers understanding of spatial distribution of ship emissions, which is important to understand the location where emissions take place.

The Ship Emissions Assessment (SEA) model was developed which is applicable for rapid ship emission estimates and identification of the spatial distribution of emissions. The SEA model uses a computational method that does not require special software or equipment. Data is obtained through widely available AIS systems, combining historic spatial ship tracks (ship movement density) and calls to port information.

The SEA model was tested to estimate emissions for 20 ship to port calls. Results were compared to the conventional IMO method [6] for bottom up emissions estimate. Aggregated results obtained by the SEA model, expressed in tonnes of CO_2, compare well, with under 5% difference to results from conventional methodology.

The SEA model was further used to calculate emissions of CO_2, SO_x and NOx and was applied to the Port of Trieste, for one ship type – containerships. Historic ship tracks, for 2017, were used to identify length of shipping lanes, and locations of ship activity phases. Port calls data for 2019 is used to analyse 377 calls to the port. Emissions were calculated for all voyages (entry and exit from 15nm port boundary).
Results show different contribution to emissions by ship engine types, using Tier III engine classification. The Port of Trieste has major pollution (75%) coming from Tier 0 and Tier I generation of ships.

Data was gathered from Marine Traffic and Clarkson's systems, that process AIS real time ship calls to a satellite tracking system and offer historic ship voyage and calls to ports data. The novelty of the SEA methodology is that spatial historic ship track maps are used to back calculate average distances, typical for ship types, to understand emissions.

The SEA model can therefore provide rapid estimates of emissions, for large ship voyage datasets, typically needed for Port emission estimates and understanding of impact of emissions spatially.

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